

Study of Proton Expansion in (p,2p) Quasielastic Scattering at Large Transverse Momentum

Alan S. Carroll

Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973

(Dated: February 24, 2003)

The measured nuclear transparencies in targets of Li, C, Al, Cu and Pb at incident momenta of 6, 10, and 12 GeV/c have been used to study the rate of proton expansion connected with (p,2p) quasielastic scattering at large momentum transfer. Simple models with linear or quadratic expansion of the effective cross section fail to simultaneously fit the measured transparencies at all three momenta. If only the 6 and 10 GeV/c transparencies are fitted, satisfactory representations can be obtained when the expansion distances for protons at 6 GeV/c are greater than 6.4 fm(linear) and 4.0 fm(quadratic). These distances are greater than those suggested by most Expansion models except the quadratic 'naive expansion' picture. However, the transparencies are well represented by the Nuclear Filtering model with no explicit expansion.

PACS numbers: 13.85.Dz, 14.20.Dh, 24.10.Lx, 24.85.+p

I. INTRODUCTION

Nuclear transparency is the experimental measure of the ability of hadrons to penetrate nuclear matter. The measured quantity is the ratio of the integrated quasielastic(q.e.) scattering cross section in a nucleus to that measured under the same kinematic conditions in a free elastic scattering. For proton-proton(p,2p) scattering the transparency, T , equation is,

$$T = \frac{\frac{d\sigma}{dt}[(p,2p) \text{ q.e. in nucleus}]}{Z \frac{d\sigma}{dt}[(p,2p) \text{ free elastic}]} \quad (1)$$

where Z equals the number of protons in the nucleus. Mueller and Brodsky suggested that the transparency would be increased compared to a Glauber calculation whenever the hadrons involved had undergone a q.e. scattering at large momentum transfer [1],[2]. This was because the scaling laws of large angle scattering suggested that the valence quarks in the hadrons, were in a point like configuration (plc) at the time of interaction. This concept is generally referred to a color transparency(CT) since the QCD interaction is considerably reduced by the near proximity of the quark color charges in the plc. Then for high momenta, the hadrons would expand sufficiently slowly over distances compared to nuclear radii to produce an anomalously high transparency compared to that predicted by standard Glauber models. The transparency would approach 1.0 as the momentum was increased.

A series of measurements at the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory of (p,2p) q.e. interactions have consistently indicated significant changes in transparency with incident momentum for scattering near 90° in the c.m. [3], [4], [5].

Ralston, Pire and Jain view the q.e. process differently [6],[7], [8], [9]. In their picture the nuclear medium strongly attenuates the large transverse portion of the pp scattering amplitude. Nuclear Filtering is a process which is constant throughout the nuclear volume, and

results in a reduced, but non-expanding hadron size. Detailed descriptions of their calculations can be found in Ref. 6 and Ref. 9.

It should be noted that the increasingly accurate (e,e'p) transparency measurements at SLAC and Jefferson Laboratory have shown no significant increase in transparency with increasing Q^2 [10], [11], [12]. The difference between the (p,2p) and (e,e'p) transparencies is likely to be a reflection of the greater complexity of the (p,2p) amplitudes.

An initial study by Heppelmann suggested that the transparencies of AGS Experiment E834 could be described by an effective attenuation cross section which was smaller than the free space value and constant in value [13]. The measurements of AGS E834 for (p,2p) q.e. scattering on nuclei ranging from Li to Pb provide a unique opportunity to measure this expansion directly in a way that has not been done previously [3]. The purpose of this paper is to make a quantitative comparisons of these two classes of models(Expansion and Nuclear Filtering) in as fair an analysis as possible with the existing data from these (p,2p) transparency experiments. Other analysis have emphasized the energy dependence, but this analysis is centered on the A dependence of the transparency at 6 and 10 GeV/c. Expansion models have generally predicted expansion distances for these AGS experiments to be comparable to nuclear radii.

II. DATA

A series of measurements made at the Alternating Gradient Synchrotron (AGS) have determined nuclear transparencies for a number of different momenta and nuclei. These measurements of (p,2p) q.e. scattering in nuclei indicated effective cross sections for absorption in nuclei, which vary with incident momenta from 6 to 14 GeV/c, and are in general significantly less than the measured pN total cross sections. The Carbon transparencies as a function of incident momentum for the 1998 data from

E850 by Leksanov, et al [5] and the 1994 data from E850 by Mardor, et al [4], and the 1987 data from E834 by Carroll, et al [3] are shown in Figure 1. Also included are the 1987 Al data from E834 which has been scaled as $(27/12)^{1/3}$ to indicate the approximate consistency of these two nuclei.

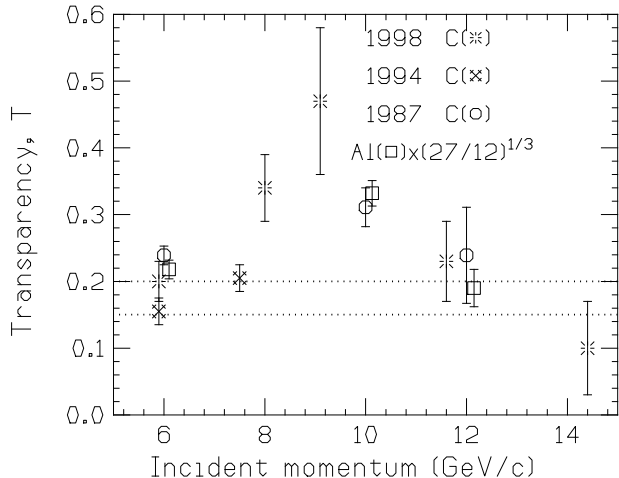


FIG. 1: Summary of Nuclear Transparency ($p, 2p$) Measurements on Carbon and scaled measurements on Aluminum (with small horizontal displacements for clarity). The dotted horizontal lines indicate the range of Glauber calculations

In particular, the publication of the data from the 1987 experiment reported on nuclear transparency values of Li, C, Al, Cu and Pb with natural isotopic abundances at incident momenta of 6 and 10 GeV/c, and C and Al at 12 GeV/c [3]. Measurements with all the targets indicated a clear increase in the transparency between 6 and 10 GeV/c. At 12 GeV/c, the transparency of the C and Al nuclei was consistent with that at 6 GeV/c as shown in Fig 2. Subsequent measurements with the new EVA spectrometer (E850) confirmed the transparencies for the C targets and expanded the range of momentum [5].

All the transparency values for the 5 nuclei from E834 as plotted in Fig 1 and Fig 2 have been multiplied by a factor of 0.724. This factor arises from the different methods for determining the transparencies in the two experiments. In E850, the transparency ratio was measured in a small region of the longitudinal light cone momentum, $\alpha = 1.00 \pm 0.05$, corresponding to the struck proton being nearly at rest in the nucleus [4],[5]. Then the total transparency was calculated using a parameterization of the complete Carbon spectral function [14]. For E834, the transparency was calculated using measurements of the transparency from essentially the entire range of α . The extraction of the transparencies involved a convolution with the spectral functions measured by the E834 experiment, and a correction for the energy dependence of the elementary pp differential cross section [3]. The measured spectral functions used in the analysis of the

E834 should correctly determine the relative transparencies of the 5 nuclei, even though the procedure of E850

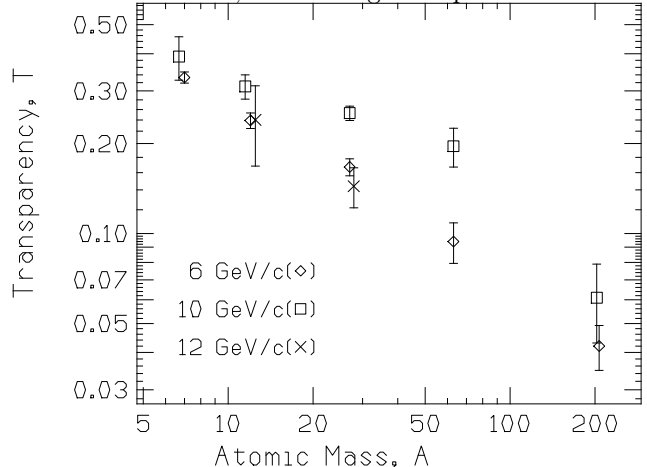


FIG. 2: Transparency vs Atomic mass A for ($p, 2p$) Measurements.

is felt to give a better absolute normalization. Since the analysis of this paper includes a floating normalization, the change should have little impact on the fitted results.

Although the 12 GeV/c data are included for completeness, the fact that the 12 GeV/c transparencies are measured for only two adjacent nuclei with rather large errors means that the results are not strongly influenced unless all three momenta are tightly coupled through an Expansion picture.

III. PARAMETERIZATION OF EXPANSION

Two general classes of models have been developed to explain the behavior of hadronic interactions inside a nuclear medium. In the Expansion class of models, the high p_t interaction is presumed to select nearly point like configurations (plc's) of valence quarks in the the interacting protons.[1] These plc's proceed to expand as their distance increases from the point of interaction.

The second class of models emphasizes that in the nuclear medium, the major effect is to strongly attenuate the large transverse portion of the proton wave function. This Nuclear Filtering picture is primarily the work of Jain, Ralston, Pire [7],[6]. This model suggests that the effective cross section will be smaller than that of the free cross sections, and remain essentially constant as it passes through the nucleus.

The rate of expansion has been described in both partonic and hadronic representations [15],[16]. Farrar, Liu, Frankfurt, and Strikman suggested the expansion parameterization for the effective interaction cross section, $\sigma_{eff}(z, Q^2)$ given by Eq 2 [15]. This form is a convenient one for this study:

$$\sigma_{eff}(z, Q^2) = \sigma_{eff}^\infty \left(\left[\left(\frac{z}{l_h} \right)^\tau + \left(\frac{r_t(Q^2)^2}{r_t^2} \right) \left(1 - \left(\frac{z}{l_h} \right)^\tau \right) \right] \theta(l_h - z) + \theta(z - l_h) \right) \quad (2)$$

where l_h is the expansion distance of the protons, and z is the distance from the interaction point. $\sigma_{eff}(z, Q^2)$ expands linearly or quadratically from its initial size depending on the value of τ , and then assumes the free space value, σ_{eff}^∞ , when $z = l_h$. As noted below, the actual value of σ_{eff}^∞ used in the fitting procedure may be less than the free σ_{tot} (pN) for the proton-nucleon interaction because a portion of the q.e. events with an initial or final state elastic scattering fall within the kinematical definition of a q.e. event. Since all the measurements are made near 90° in the c.m., $Q^2 \sim p_0$.

The exponent τ allows for three suggested pictures of expansion; $\tau = 0, 1$, and 2 . For $\tau = 1$, the expansion corresponds to the ‘‘quantum diffusion’’ picture [15]. For this picture, $l_h = 2p_f/\Delta(M^2)$ where p_f is the momentum of a proton traveling through the nucleus and $\Delta(M^2)$ is the mass difference of an intermediate state [15]. At distances comparable to nuclear sizes, the effective cross sections should revert to their free space values. The authors of [15] indicate the values of $\Delta(M^2)$ between 0.5 and 1.1 GeV^2 are acceptable with $\Delta(M^2)=0.7$ being favored. This range of $\Delta(M^2)$ corresponds to values of $l_h = 0.36p_f$ to $0.78p_f$ fm. For a momentum of $6 \text{ GeV}/c$ the expansion distance will be between 2.1 and 4.7 fm. For convenience of calculation in this paper an expansion parameter, λ , scaled to $6 \text{ GeV}/c$ has been used to parameterize all the proton momenta in the interaction for each incident momentum. That is the expansion distance l_h for each leg of the calculation shown in Fig 3 is given by $l_h = \lambda(p_f/6) \text{ fm}$.

The case of $\tau = 2$ is generally referred to as the ‘naive quark expansion’ scenario in which the light quarks fly apart at a maximum rate and the distance is determined by the Lorentz boost to the hadrons. In this case $l_h \sim E/m_h$ where m_h is the mass of the hadron involved [15]. For protons at $6 \text{ GeV}/c$, λ equals $\sim 7.3 \text{ fm}$.

The quantity $\langle r_t(Q^2)^2 \rangle / \langle r_t^2 \rangle$ represents the fraction of σ_{eff} at the time of interaction. This quantity is approximated by $\sim 1/Q^2$, corresponding to 0.21 at $6 \text{ GeV}/c$ and falling with an increase of incident momentum [15]. Variations of this value have only a small effect on the result. A recent analysis by Yaron, et al repeats this analysis with $\tau = 1$ and obtains very similar results [17].

Given that the initial and final states in these (p,2p) q.e. interactions are exclusive hadrons, the approach of Jennings and Miller to represent the proton expansion in terms of a set of hadronic states seems very reasonable [16],[18]. This representation explicitly notes that a plc cannot be a simple proton, but must include a superposition of excited states. When this spectrum of intermediate states, $g(M_X^2)$, is described by a power law

falloff, then the expansion has a linear form, $\tau = 1$, with $\lambda \sim 0.9 \text{ fm}$ [16]. With a sharp cutoff of M_X^2 at $\sim 2.2 \text{ GeV}^2$, then σ_{eff} grows quadratically with $\lambda \sim 2.4 \text{ fm}$ [16]. The form of these expansions can be approximated by that given in Eq. 2.

Because in the Nuclear Filtering picture, the long distance portion of the amplitude has been filtered away by the nuclear medium, the cross section for q.e. scattering in the nucleus will follow the scaling behavior, whereas the unfiltered free pp cross section will show oscillations about the s^{-10} scaling. Thus the variations in the nuclear transparency are mainly due to the oscillations in the free pp cross section about the cross section with exact scaling. In fitting the transparency, no expansion should be required, only a smaller effective cross section. In this model of the second class, τ is set to 0 , so Eq. 2 reduces to,

$$\sigma_{eff}(z, Q^2) = \sigma_{eff}(Q^2). \quad (3)$$

Also $\sigma_{eff}(Q^2)$ is allowed to vary over an extended range of values. This analysis is very similar to that described by Jain and Ralston [19].

IV. METHOD

There seems to be no simple parameterization of nuclear transparency as a function of incident momentum (p_0), nucleus(A), effective cross section (σ_{eff}) and expansion distance (λ). So the approach taken in this paper is to calculate via Monte Carlo means the nuclear transparency at a number of closely spaced values, and then do a search to find the best fit to the experimental values.

Fig 3 illustrates the geometry and kinematics of these calculations. The integrals for the calculating the transparency at each incident momentum, p_0 and outgoing momentum, p_3 and p_4 , are given by the following expressions. Also a normalization parameter, $r_n(p_0)$, as described below, is included.

$$T(\sigma_{eff}, A, \lambda) = r_n(p_0)P_0P_3P_4 \quad (4)$$

where the average survival probabilities, P_i , of the protons on each of the three legs (i) is calculated by the integrals along each of the three paths in z from the randomly selected interaction points to the edge of the nucleus,

$$P_i = \exp \left[- \int_{path} dz' \sigma_{eff}(p_i, z, \lambda_i) \rho_A(r_i) \right] \quad (5)$$

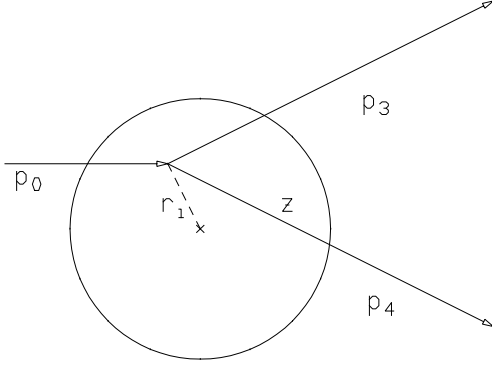


FIG. 3: Coordinates for Transparency Calculations by Monte Carlo.

A Woods-Saxon form was used for the density, $\rho(r_i) = c/(1 + \exp(-R + r_i/b))$, where r_i is the radial distance from the nucleus center to a point along the i^{th} path. The parameter b is set to 0.56 fm, and then the $\langle rms \rangle$ radii were matched to electron scattering results [20]. The integrated density was normalized to be equal to the A of the nucleus. The calculated Carbon transparencies are in agreement with Glauber calculations of the Carbon transparency of 0.15 to 0.20 for σ_{eff} between 36 and 40 mb by a number of other authors [21],[22],[23]. Since

this approach is deeply related to the Glauber theory similar results from that method can be expected. The Expansion model uses a classical cross section, and it is best that it be tested on the same basis as it was formulated. Note that this agreement with the Glauber calculation for the Carbon nucleus alone does not imply agreement with a A dependence for all 5 nuclei. The effect of correlations on the calculated transparencies and the fitted results is discussed in the Appendix following Lee and Miller [23].

The transparency was calculated for the 5 different nuclear targets in 1 mb steps of σ_{eff} from 1 to 51 mb, and at 14 values of λ from 0 to 50 fm. Then the calculated transparencies at each value of A , p_0 , and σ_{eff} are parameterized with an empirical four parameter function in λ , $T(\lambda) = \alpha + (1 - \alpha)e^{[\beta/(zc+\lambda)]} - \gamma\lambda$, for use in fitting to the measured transparencies. Note that the λ value couples the expansion between 6, 10, and 12 GeV/c. The 1000 trials generated for each point resulted in a statistical accuracy of ± 0.01 in the calculated transparency values. As an illustration, a sample of the calculated transparency values for 10 GeV/c is given in Table I.

Using the generated values of the transparency, a best fit was made to the values for 6, 10, and 12 GeV/c. The random search was made by interpolating between σ_{eff} values for the 5 different nuclei, and calculating the fitted $T(\lambda)$ function. The search determined the best fit from minimizing the χ^2 function given in Eq. 6.

$$\chi^2 = \Sigma_{i=1}^5 S_i^2(6GeV/c) + \Sigma_{i=1}^5 S_i^2(10GeV/c) + \Sigma_{i=2}^3 S_i^2(12GeV/c) \quad (6)$$

where there are sums, Σ , for the three momenta and the 5 nuclei (2 nuclei at 12 GeV/c). The terms for each momentum (k) and nucleus(i) are of the form:

$$S_i^2(p_k) = [(r_n(p_{0,k})T_i(fit) - T_i(meas))/(\Delta T_i(meas))]^2 \quad (7)$$

Note that in addition to the values in the table of generated transparencies, relative normalization factors for each incident momentum, $r_n(p_{0,k})$, are included to allow for normalization uncertainties in both the data and the uncertainties of the phenomenological transparency calculations for each incident momentum (k). A similar factor was used in the analysis of Jain and Ralston [19]. The search procedure used for each value of λ in steps of 1.0 from 0 to 20 was straightforward. Values for σ_{eff} and $r_n(p_{0,k})$ were randomly selected for the entire range of possible values, and then the values which yielded the smallest fitted χ^2 were selected. For the Expansion models, the values σ_{eff} at 6, 10 and 12 GeV/c are constrained to be equal, and to the values of $r_n(p_{0,k})$ are allowed to vary by up to $\pm 15\%$ with respect to each

other to allow for relative normalizations. The fitting procedure was applied to both the sets of transparencies at 6, 10 and 12 GeV/c, and the set containing only 6 and 10 GeV/c transparencies. A 4×10^5 trial coarse search over the full range of variables was followed by a 6×10^5 trial fine search within 10% of the final values. Repeated applications of this procedure yielded fits, which varied by at most 1%. The quality of the fits is indicated by the value of χ^2 .

The Expansion models assume that σ_{eff} returns to its free space values at some distance. At the incident momenta of this experiment, that distance is expected to be comparable to the radius of the heavier nuclei. Not all of the elastic scattering cross section ($\sim 8mb$ out of 40 mb) should be included in σ_{eff} because the kinematics of some of the q.e. events with initial and final state elastic scattering reconstruct within the Fermi distribution of ~ 250 MeV/c. A Monte Carlo study of the experimental acceptance of E834 indicates that only 2.5 ± 1.0 mb of the elastic cross section should be included. For purposes of this study, all σ_{eff} values above 32 mb have been allowed

TABLE I: Sample of calculated transparency values for 10 GeV/c with an initial $\sigma_{eff} = 0.117\sigma_{eff}^{inty}$.

A	p_0 GeV/c	σ_{eff} mb	λ fm	Transp T
7.0	10.0	1.00	0.00	0.9603
7.0	10.0	1.00	0.50	0.9636
.
.
.
12.0	10.0	19.00	13.50	0.7645
12.0	10.0	19.00	16.50	0.7811
12.0	10.0	19.00	50.00	0.8387
.
27.0	10.0	19.00	0.00	0.2373
27.0	10.0	19.00	0.50	0.2542
27.0	10.0	19.00	1.00	0.2838
27.0	10.0	19.00	1.50	0.3227
27.0	10.0	19.00	2.50	0.3597
27.0	10.0	19.00	3.50	0.4194
27.0	10.0	19.00	4.50	0.4652
27.0	10.0	19.00	5.50	0.5126
27.0	10.0	19.00	6.50	0.5401
27.0	10.0	19.00	7.50	0.5750
27.0	10.0	19.00	10.50	0.6156
27.0	10.0	19.00	13.50	0.6548
27.0	10.0	19.00	16.50	0.6850
27.0	10.0	19.00	50.00	0.7691
.
63.5	10.0	19.00	0.00	0.1368
63.5	10.0	19.00	0.50	0.1624
.
.
.
207.2	10.0	51.00	16.50	0.1011
207.2	10.0	51.00	50.00	0.2116

in the fitting procedure for the Expansion models so that the result is not dependent on the precise magnitude of the elastic cross section included. The maximum σ_{eff} allowed, 45 mb, is well beyond the maximum expected.

For the fit with the Nuclear Filtering model, the parameter, τ is set to 0, and σ_{eff} is allowed to vary from 1 to 45 mb at each incident momenta.

V. RESULTS

Fig. 4 gives the result of fitting the transparencies to the linear ($\tau = 1$) Expansion hypothesis. As stated above, the values of σ_{eff} are constrained to be greater than 32 mb, and equal in magnitude at each step in λ . The values of $r_n(p_{0,k})$ are held to be within $\pm 15\%$ of

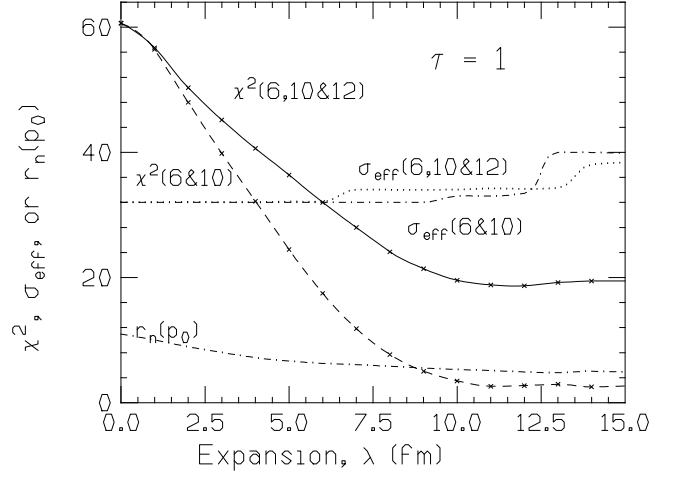


FIG. 4: The χ^2 and fitted parameters for a fit to transparencies with linear Expansion model ($\tau = 1$). σ_{eff} is given in mb. The normalization parameter, $r_n(p_0)$, have been multiplied by 10.

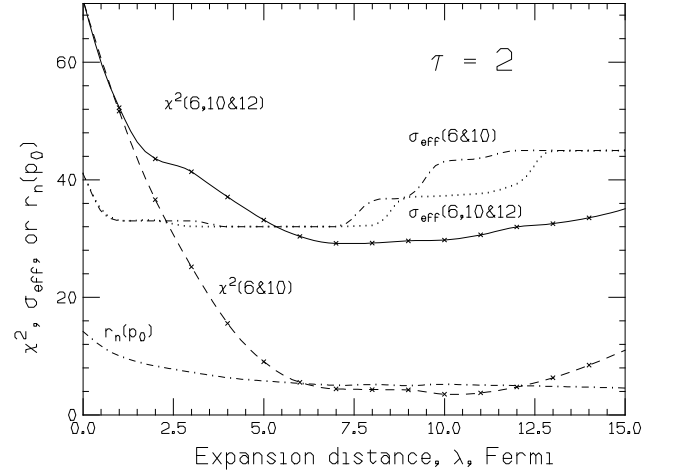


FIG. 5: Fit to transparencies with quadratic Expansion model ($\tau = 2$). The meaning of the curves is the same as in Fig 4.

each other at each step. The solid curve starting at ~ 60 corresponds to χ^2 in the fit to the 6, 10 and 12 GeV/c transparencies. The minimum value of this χ^2 curve is 19 which has a probability of 1.5%. The upper dot-dash curve gives the fitted value for σ_{eff} which stays at the minimum value of 32 mb for $\lambda < 6$ fm. The lower dot-dash line corresponds to $r_n(p_{0,k})$ multiplied by 10. $r_n(p_{0,k})$ falls from a value of ~ 1.0 at $\lambda=0$ fm to 0.5 at larger expansion distances. The values of $r_n(p_{0,k})$ are held to within 15% of one another.

The dashed curve in Fig 4 starting at ~ 60 is the χ^2 for fitting only the 6 and 10 GeV/c transparencies. The probability of χ^2 reaches 5% for values of λ greater than 6.4 fm. The dotted curve traces the behavior of σ_{eff} for this fit. The values of $r_n(p_{0,k})$ are very similar in both cases.

The results of fitting to the quadratic expansion ($\tau =$

TABLE II: Parameters for Nuclear Filtering ($\tau = 0$) case with 8 DoF. With no constraint on $r_n(12\text{GeV}/c)$ the value of $\sigma_{eff}(12\text{GeV}/c)=19^{+21}_{-15}$ mb.

$r_n(6\text{GeV}/c)$	0.63 ± 0.02
$\sigma_{eff}(6\text{GeV}/c)$ (mb)	$17.9^{+2.7}_{-1.5}$
$r_n(10\text{GeV}/c)$	0.65 ± 0.02
$\sigma_{eff}(10\text{GeV}/c)$ (mb)	$12.3^{+2.6}_{-2.6}$
$r_n(12\text{GeV}/c)$	0.59 ± 0.02
$\sigma_{eff}(12\text{GeV}/c)$ (mb)	$19.0^{+8.9}_{-3.5}$
χ^2	3.77
$Prob(\chi^2)$	87%

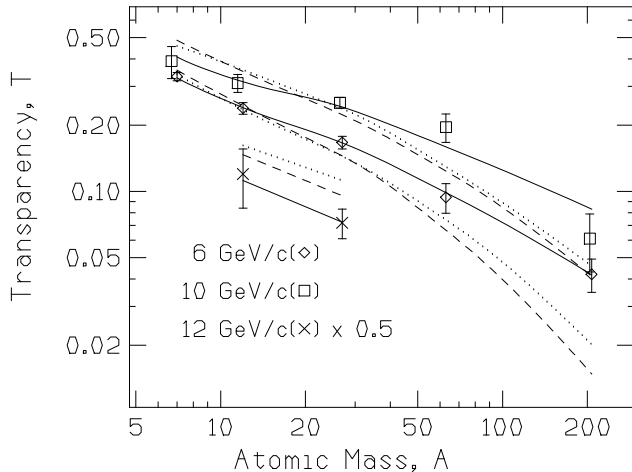


FIG. 6: Representative fits to transparencies. The Nuclear Filtering model $\tau = 0$ is represented by the solid curves, and the $\tau = 1$ and $\tau = 2$ Expansion models at $\lambda = 3$ fm are displayed as the dashed and dotted curves respectively. Note that the 12 GeV/c transparencies have been multiplied by 0.5 to avoid overlap with the 6 GeV/c results.

2) are shown in Fig 5. The curves have the same meaning as in Fig 4. χ^2 for the fit to the 6, 10 and 12 GeV/c transparencies (solid curve) never goes below 29.2, corresponding to a probability of less than 0.012. For the case of a fit to only the 6 and 10 GeV/c data (dashed curve), the probability reaches 5% at $\lambda=4.0$ fm.

Table II displays the values of a fit with Nuclear Filtering ($\tau = 0$). Here the values of σ_{eff} are allowed to vary independently at each momenta without constraints on the minimum value of σ_{eff} . However, the values of $r_n(p_{0,k})$ are again constrained to remain within $\pm 15\%$ of each other. The overall χ^2 of 3.77 indicates a probability of 87% for 8 DoF. The errors are determined from the one standard deviation in the $\ln(\text{Likelihood})$ [24]. Jain and Ralston found values of 17 ± 2 mb and 12 ± 2 mb for $\sigma_{eff}(6\text{GeV}/c)$ and $\sigma_{eff}(10\text{GeV}/c)$ which are consistent those in Table II [19].

Fig. 6 illustrates the quality of the fit to the experimentally measured transparencies for each of the 5 nuclei at 6, 10, and 12 GeV/c for the 3 models; namely for $\tau = 0$ for

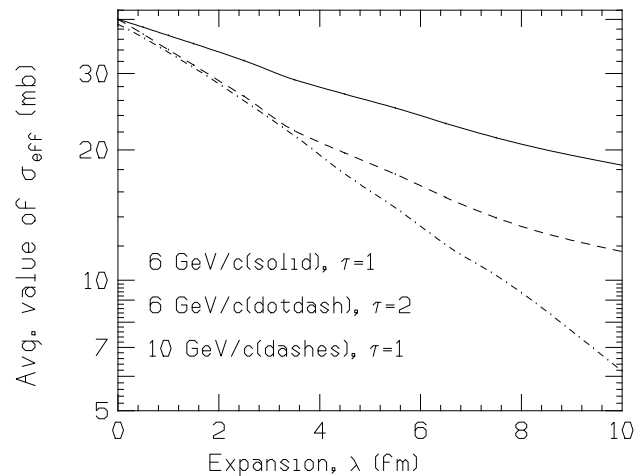


FIG. 7: Average σ_{eff} vs λ for Aluminum .

the Nuclear Filtering model, and $\lambda=3$ fm for $\tau = 1$ and $\tau = 2$. At this expansion distance, the $\tau = 1$ and $\tau = 2$ Expansion models indicate a fall off of transparency with A which is much steeper than that measured. Generally reasonable fits can be made with the $\tau = 1$ and $\tau = 2$ expansion models to the 6 and 10 GeV/c transparencies alone when λ is greater than 6 fm. However, only the Nuclear Filtering (solid curve) can simultaneously fit to the 6, 10 and 12 GeV/c transparencies.

VI. CONCLUSIONS

Table III presents a summary of this analysis, and predictions of various models. Due to the oscillatory nature of the (p,2p) transparency with incident momentum, it is not surprising that no acceptable fit with $Prob(\chi^2) > 0.05$ can be achieved with a simple, unified Expansion model simultaneously fitting to the data at 6, 10 and 12 GeV/c. As has been noted by various authors, additional amplitudes are needed to account for the sudden drop in transparency between 10 and 12 GeV/c. This measured drop in the transparency has been verified by the E850 experiment, and is shown in Fig 1 to continue to higher momenta [5].

For Ralston and Pire, the drop in transparency is connected with the interference of the short distance pQCD amplitude with that of the long distance Landshoff contribution [7]. Brodsky and deTera mond [25] noted the strong correlation in energy between the striking spin dependence of pp scattering [26] and the behavior of the (p,2p) transparency [3]. They suggested that the drop in transparency at 12 GeV/c could be due to the presence of a resonance in the pp channel creating a long-range amplitude. This resonance could be connected with the threshold of charm particle production [25].

One might imagine that the 6 and 10 GeV/c transparencies represent a simpler set of data where only one set of amplitudes dominate. Thus a simple Expansion

TABLE III: Summary of Fit Parameters and Comparison to Models

This Analysis	$\tau = 0$	$\tau = 1$	$\tau = 1$	$\tau = 2$	$\tau = 2$
Momenta Fit	6, 10&12	6&10	6, 10&12	6&10	6, 10&12
Prob(χ^2)	0.87	> 0.05	< 0.044	> 0.05	< 0.012
.	const.	for	for	for	for
λ, fm		> 6.4	All	> 4.0	All
$\sigma_{eff}(6\text{GeV}/c), \text{mb}$	$17.9^{+2.7}_{-1.5}$				
$\sigma_{eff}(10\text{GeV}/c), \text{mb}$	$12.3^{+2.6}_{-2.6}$				
Farrar, et al					
Prob(χ^2)		$1 \times 10^{-7} - 8 \times 10^{-4}$	$3 \times 10^{-7} - 5 \times 10^{-5}$	0.82	1×10^{-3}
λ, fm		2.1 - 4.7	2.1 - 4.7	7.3	7.3
Jennings - Miller					
Prob(χ^2)		2×10^{-9}	1×10^{-8}	1×10^{-4}	6×10^{-6}
λ, fm		0.9	0.9	2.4	2.4

hypothesis could be satisfied. This is the motivation for showing how the Expansion models fit the 6 and 10

GeV/c data alone.

Since there are values of λ for which the 6 and 10 GeV/c data alone can be satisfactorily fit, it is interesting to consider whether these values of λ agree with various models. The maximum value of expected value of λ for the linear ($\tau = 1$) expansion corresponds to an intermediate mass, $\Delta(M^2)=0.5 \text{ GeV}^2$, corresponding to $\lambda=4.7 \text{ fm}$ at 6 GeV/c [15]. At this value Prob(χ^2) is 8×10^{-4} . The hadronic model suggests that $\lambda=0.9 \text{ fm}$ [16],[18]. Thus no linear Expansion pictures in either the partonic or hadronic representations provide expansions long enough to fit the data.

The curves of Fig 7 show a calculation of the average value of σ_{eff} over the path lengths in the Al nucleus for a range of expansion parameters, λ . At expansion distances of $\sim 6 \text{ fm}$, the average σ_{eff} approaches the fitted values of σ_{eff} in the $\tau = 0$ case indicating how the large values of λ yield acceptable fits in the case of expansion.

For the $\tau = 2$ expansion, an acceptable fit to 6 and 10 GeV/c is reached at a smaller value of λ due to the more rapid fall off of σ_{eff} with λ (see Fig 7). The Prob(χ^2) becomes 5% at 4.0 fm which is within the range of $\lambda=7.3 \text{ fm}$ suggested by the 'naive Expansion model' [15]. In the hadronic representation of Jennings and Miller, a quadratic expansion has a λ of 2.4 fm [16] which has a probability of 1×10^{-4} .

The Nuclear Filtering picture is favored by this analysis. There is a different constant value of σ_{eff} each incident momentum, and hence Q^2 . However, σ_{eff} shows no expansion over range of nuclear radii from Li (2.1 fm) to Pb (6.6 fm) and provides an acceptable description of the data as has been shown in previous publications[13],[9]. Both linear and quadratic expansion pictures fail to fit

the entire set of data. Fits to the limited 6 and 10 GeV/c data set are achieved for linear expansions which are beyond the range of a variety of models. The quadratic expansion ($\lambda \sim 7.3 \text{ fm}$) in the naive quark picture can provide an acceptable fit to the 6 and 10 GeV/c data, but the theoretical basis for such simple behavior seems weak. However, as indicated in Fig. 7, the quadratic fit confirms the need for a small σ_{eff} .

For future (p,2p) experiments it would be very interesting to measure the A dependence for an incident momentum in the range of 12 to 14 GeV/c where the transparency is at a minimum. According to the Jain, Pire and Ralston picture[9], the value of σ_{eff} should continue to decrease even though the transparency has fallen by about of factor of two from its C value at 9 GeV/c.

Acknowledgments

I am pleased to acknowledge the dedicated efforts of all my collaborators on E834[3] and E850[4],[5]. In particular, I would like to express my appreciation to my co-spokesman, S. Heppelmann; my Brookhaven colleagues, D. Barton, G. Bunce, and Y. Makdisi; H. Nicholson of Mt Holyoke College; and my collaborators from Tel Aviv, J. Alster and E. Piasetzky. The helpful discussions with P. Jain and J. Ralston were greatly appreciated. Improvements to the text were generated by the careful proof reading of Y. Makdisi.

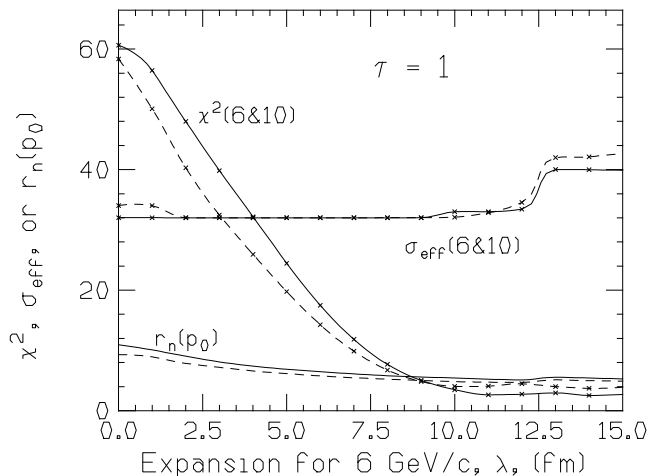


FIG. 8: Result of fitting with Correlations (solid lines) and without Correlations(dashed lines)

APPENDIX: EFFECT OF CORRELATIONS

The Monte Carlo calculations of transparencies were adjusted to match existing Glauber calculations of C

transparency. Explicit correlation effects were not included in the calculations of this paper. See Ref [27] for a discussion of correlation effects. As a check, some of the calculations were repeated using the formulation of Lee and Miller [23]. These correlations indicate the nuclear density seen by the outgoing protons is reduced for a distance of $\sim 1 fm$ in the vicinity of the struck proton. A comparison of the results for the linear expansion($\tau = 1$) with and without the correlation correction for the 6 and 10 GeV/c fit is shown in the Fig 8.

As can be seen there is little difference in the parameters or the quality of the fit. The correlations increase the transparencies by ~ 0.05 for C and ~ 0.005 for Pb at $\lambda = 5 fm$. A small adjustment (0.688 to 0.616 for $\lambda = 5 fm$) of the normalization parameter, $r_n(p_{0,k})$, suffices to achieve nearly the same χ^2 .

Thus the conclusion is reached that the results are not very sensitive to the exact form of the nuclear density.

-
- [1] A. Mueller. *Proceedings of the XVII Rencontre de Moriond, edited by J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, France, 1982).* 1982.
 - [2] S. J. Brodsky. *Proceedings of the XIII International Symposium on Multi-particle Dynamics-1982, edited by W. Kittel, W. Metzger, and A. Stergiou (World Scientific, Singapore, 1982).* 1983.
 - [3] A. S. Carroll, et al. *Phys. Rev. Lett.*, 61:1698, 1988.
 - [4] I. Mardor, et al. *Phys. Rev. Lett.*, 81:5085, 1998.
 - [5] A. Leksanov, et al. *Phys. Rev. Lett.*, 87:212301-1, 2001.
 - [6] P. Jain, B. Pire, and J. P. Ralston. *Phys. Rep.*, 271:67, 1996.
 - [7] J. P. Ralston and B. Pire. *Phys. Rev. Lett.*, 61:1823, 1988.
 - [8] J. P. Ralston and B. Pire. *Phys. Rev. Lett.(Comment)*, 67:2112, 1991.
 - [9] P. Jain and John P. Ralston. *Phys. Rev. D*, 46:3807, 1992.
 - [10] K. Garrow, et al. *Phys. Rev. C*, 66:044613, 2002.
 - [11] N.C.R. Makins, et al. *Phys. Rev. Lett.*, 72:1986, 1994.
 - [12] T.G. O'Neill, et al. *Phys. Lett. B*, 351:87, 1995.
 - [13] S. Heppelmann. *Nuc. Phys.B(Proc Suppl)*, 12:159, 1990.
 - [14] C Ciofe degli Atti and S. Simula. *Phys. Rev. C*, 53:1689, 1988.
 - [15] G. R. Farrar, H. Liu, L. L. Frankfurt, and M. I Strikman. *Phys. Rev. Lett.*, 61:686, 1988.
 - [16] B. K. Jennings and G. A Miller. *Phys. Rev. Lett.*, 69:3619, 1992.
 - [17] I. Yaron, L. Frankfurt, E. Piasetzky, M. Sargsian, and M. Strikman. *Phys. Rev. C*, 66:024601, 2002.
 - [18] B. K. Jennings and G. A Miller. *Phys. Lett. B*, 318:7, 1993.
 - [19] P.K. Jain and J. P. Ralston. *Phys. Rev. D*, 48:1104, 1993.
 - [20] H. DeVries, C. W. de Jager, and C. De Vries. *At. Data Nucl. Data Tables*, 36:495, 1987.
 - [21] L. L. Frankfurt, M. I Strikman, and M. B. Zhalov. *Phys. Rev. C*, 50:2189, 1994.
 - [22] L. L. Frankfurt, M. I Strikman, and M. B. Zhalov. *Phys. Lett. B*, 503:73, 2001.
 - [23] T-S H. Lee and G. A. Miller. *Phys. Rev C*, 45:1863, 1992.
 - [24] Particle Data Group. *Phys. Rev. D*, 54:160, 1996.
 - [25] S. J. Brodsky and G. de Teramond. *Phys. Rev. Lett.*, 60:1924, 1988.
 - [26] E. A. Crosbie, et al. *Phys. Rev. D*, 23:600, 1981.
 - [27] L. L. Frankfurt, E. J. Moniz, M.M. Sargsyan, and M. I Strikman. *Phys. Rev. C*, 51:3435, 1995.